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Quantitative appraisal of biomass resources and their energy potential in Egypt

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ABSTRACT

The utilization of biomass as a renewable source of energy is important from the energetic as well as the environmental viewpoint. It can reduce the rate of fossil fuel depletion caused by the rapid increase in energy consumption. This paper presents an estimation of the biomass and its potential energy in Egypt. Four main types of biomass energy sources are included: agricultural residues (dedicated bioenergy crop residues), municipal solid wastes, animal wastes, and sewage sludge. The potential biomass quantity and its theoretical energy content were computed according to statistical reports, literature reviews, and personal investigations. The results show that Egypt produces a considerable amount of biomass with a total theoretical energy content of 416.9×10^{15} J. The dry biomass produced from bioenergy crop residue sources has been estimated at about 12.33 million tons/year, of which 63.75% is produced from rice straw. This source represents the highest percentage (44.6%) of the total theoretical potential energy in Egypt, followed by municipal solid wastes, which could produce 41.7% from an annual amount of 34.6 million tons. Meanwhile, the rest of the total theoretical potential energy could be produced from animal and sewage wastes. The estimated biomass with its considerable potential energy content represents an important renewable energy source in Egypt.

Contents

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1. Introduction

Widespread and massive consumption of fossil fuels has led to rapid economic growth in advanced industrial societies but has also increased carbon dioxide in the atmosphere and consequently caused global warming and climate change. Renewable energy sources should replace fossil fuels fundamentally and structurally; they are receiving worldwide attention and will play an important role in meeting the future needs of the world [1,2]. Renewable energy sources are natural resources such as sunlight, wind, biomass, and geothermal heat, which are naturally replenished. Based on factors such as the availability and choice of technologies in Egypt, Khalil et al. [3] positioned wind energy and solar water heating as leading renewable energy technologies in power generation, followed by biomass technology.

Biomass represents an important source of energy which includes a large variety of different fuels with different chemical compositions and combustion characteristics. Its utilization as a source of energy is important from an energetic as well as an environmental viewpoint [4,5]. Unlike coal, CO_2 emissions from biomass are negated by the photosynthetic contribution during the growth cycle of biomass, resulting in a net zero impact on the environment [6,7]. Moreover, biomass reduces the rate of fossil fuel depletion and has the theoretical potential to supply 100% of the world's energy needs [2,8].

Due to the vital role played by the energy sector, energy demand is increasing in direct proportion to the increase in population and industrial development to satisfy technological needs and the development of lifestyles in Egypt. Primary energy demand has grown at an average annual rate of 4.64% during the last years [9]. Securing energy supply on a continuous basis is a vital element for sustained development plans, and Egypt, as a country of limited fossil fuel resources as well as growing demand for electrical energy, has given due consideration to the diversification of its energy portfolio by utilization of its renewable energy resources [10].

In Africa, about half of the energy used originates from biomass or agricultural residues [11]. A study by Smeets et al. [12] projected that Africa has the largest potential for bioenergy production by 2050 in the world: 317 exajoules (EJ) per year, which could constitute a quarter of the projected total world potential (1272 EJ per year). In this sense, during the last decade, Egypt has been one of the developing countries following successful programs for the development of renewable energy resources [13]. It produces millions of tons of biomass waste every year, which could contribute more than 151 PJ (petajoules) of primary energy [14], but nowadays these wastes are causing pollution and health problems [2]; in consequence, the incorporation of biomass with other renewable energy sources will increase the potential for solving energy and environmental problems.

However, there have been insufficient investigations regarding the production of biomass in Egypt and an analysis of existing and potential biomass sources will be required well before the start-up of large-scale production of bioenergy from this renewable fuel. As a consequence, a quantitative appraisal of biomass resources and their energy potential in Egypt represents the main objective of this study.

2. Energy situation in Egypt

2.1. Geography, climate, and energy balance in Egypt

Egypt forms the northeast corner of Africa and covers a total area of almost one million Km^2 (Fig. 1) [15]. It has hot and dry weather in summer and a warm winter with average rainfall of 50 mm/year. The inhabited part of Egypt is the 1000 km valley from Aswan to Alexandria, flanked by desert [16]. According to the Central Agency for Public Mobilization and Statistics (CAPMS) [17], Egypt has an estimated population of about 83 million in 2013.

The energy sector plays a major role in Egypt's economic development. The primary energy resources and production in Egypt are shown in Fig. 2. It is clear that crude oil is the most important, representing 53.11% of the total resources. Electricity from the High Dam in Aswan accounts for a share of about 5% and natural gas accounts for 41.89% of the total resources. On the other hand, primary production of coal accounts for only 1.6 PJ, and Egypt has to import coal. The sectoral energy consumption in Egypt is summarized in Fig. 3. The industrial sector accounts for about 46% of consumption, representing the highest value of energy consumption among the sectors [18].

Production of crude oil continues to decline despite new discoveries and improvements in oil recovery techniques at mature fields. Its production had fallen from 740 thousand barrels per day (bbl/day) in 2004 to 680 thousand bbl/day in 2009. On the

Fig. 1. Map of Egypt [15].

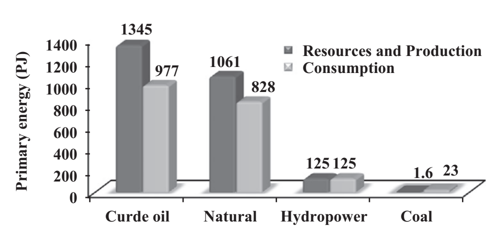

Fig. 2. Primary energy resources production and consumption in Egypt [18].

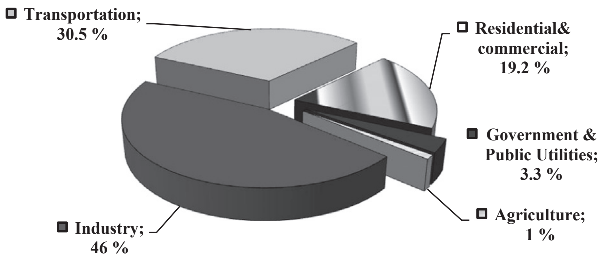

Fig. 3. Sectoral consumption of primary energy in Egypt [18].

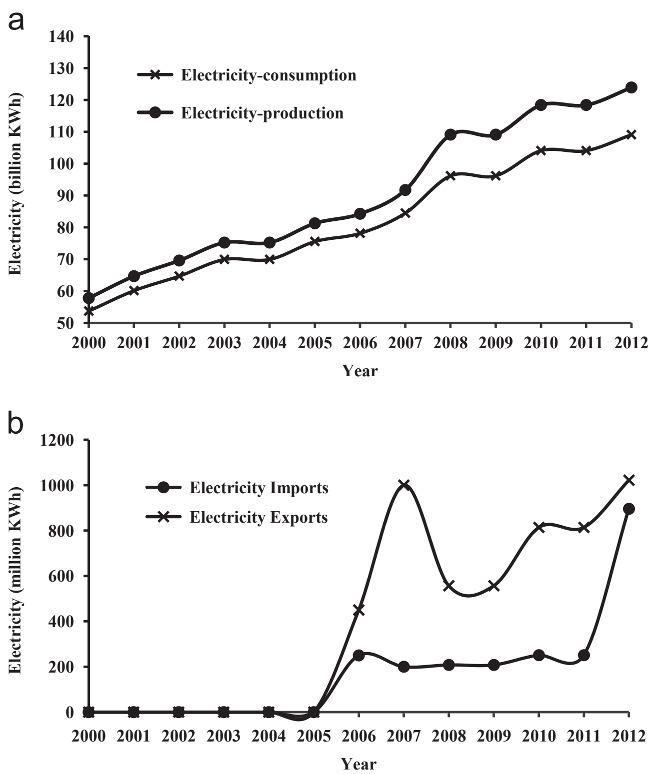

Fig. 4. Electrical energy production and consumption (a), and imports and exports by year (b) [19].

other hand, its consumption increased from 590 thousand to 683 thousand bbl/day over the same years, making the country a net importer of oil. In contrast, natural gas production continued to rise from 32.56 billion m^3 in 2004 to 62.69 billion m^3 in 2009 while its consumption increased from 31.46 to 44.37 billion m^3 over the same years, and the country became a major exporter, with its natural gas exports being estimated at 18.3 billion m^3 in 2009. The proven reserves of natural gas in 2011 were 2.2 trillion m^3 and there is growing concern among some experts that Egypt's gas reserves could be depleted as early as 2020, after which the country could face a deficit between consumption and production [19].

2.2. Electrical energy in Egypt

Electrical demand and consumption are growing rapidly in Egypt. As new industrial/residential cities and tourist complexes are built and the standard of living improves, demand for electricity is increasing at a faster rate than overall economic growth [20]. Fig. 4a shows electrical energy production and consumption from 2000 to 2012, while imports and exports of electrical energy are shown in Fig. 4b. The rapidly increasing rates of electrical energy consumption and production, whose values doubled over the last decade, can be clearly observed. The large increase in demand across all sectors is leading to high electricity generation growth rates. It has been forecast that electricity consumption will reach 250 TWh by 2020 [21].

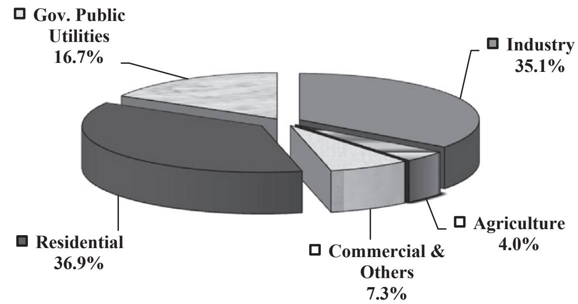

Fig. 5. Electrical energy consumption by sector in the year 2007 [22].

Fig. 5 presents the electrical energy consumption by sector for the year 2007 as a percentage of the total electrical energy consumption in Egypt [22]. The data in the figure show that the residential and industrial sectors account for the major parts of electrical energy consumption in Egypt: about 36.9% and 35.1% of electrical energy consumption, respectively. Together, the rest of the sectors account for only about 28% of total electrical energy consumption.

3. Biomass resources in Egypt

There is good potential for the utilization of biomass energy resources in Egypt. Biomass resources are currently used inefficiently, particularly agricultural residues, which are combusted in open fire stoves in villages [13]. However, real environmental benefits of biomass utilization can be achieved through large-scale application of biomass-based fuel to generate energy [23]. Consequently, Egypt has recently adopted an ambitious plan to produce 20% of its generated electricity using renewable energy resources by 2020 [10]. Biomass resources have been estimated in this study based on agricultural residues, animal wastes, sewage wastes, and solid wastes. The results are summarized in the subsections presented below.

3.1. Agricultural residues

Agricultural residues are the amount of crop that remains after the collection of the main product. Residues depend upon a wide range of local conditions and the primary factors influencing the amount of crop residue are the type and variety of crops planted and their yields [24]. The effective total cultivated area is around 6.09 million ha annually [25] and approximately 3.444 million ha of land are cultivated in Egypt, yielding crops two or three times a year. Therefore, Egypt produces millions of tons of agricultural wastes every year [2,26,27], contributing to about 50% of the total biomass potential [28].

Over 27 million tons of crop residues were generated in 2003 [29]. Types of crop residues and their estimated quantities and percentages in relation to the total residue generation are listed in Table 1. Wheat straw is the most abundant residue, followed by maize, rice straw, and sugar cane residues, respectively. Actual crop residue generation may vary by 10–15% or more in any given year. Table 1 lists the quantity and percentage of each crop residue utilized during the year 2004. At least 77.8% of the crop residues are reutilized for various purposes other than for energy generation, as shown in Table 2.

Nationally, unutilized crop residues are estimated to amount between 4.422 and 5.684 million tons. The largest amount of unused crop residue is rice straw, by a wide margin [29], followed by cotton stalks. Hamdy [30] mentioned that about 52% of agricultural residues are burnt directly on the fields or in inefficient burners (with less than 10% efficiency) in small villages. Both methods result in loss of energy as well as negative impacts on the environment. Moreover, traditional storage in farms and on roofs provides a large opportunity for insects and other disease carriers to grow and attack humans, animals, or new crops [5]. The burning of crop residues is, however, practiced by farmers, despite legal requirements [29].

3.2. Animal wastes

Animal wastes are another form of biomass used for energy generation. The amount of animal waste residue depends on the animal type, size, and population density for each location [24].

Large amounts of animal wastes are produced in Egypt. The total cattle herd (including domesticated buffalo) in 2009 was estimated at about 6.248 million head [31]. Table 3 shows that the total amount of cattle (buffalo and cow) manure is about 10.5 million tons/year [5,30], representing the majority of animal waste.

The uncontrolled handling and storage of manure causes loss of organic matter and also pollution problems. Hamdy [30] mentioned that about 60% of cattle waste is used as fuel by direct burning in low efficiency burners (less than 10%); another 20% of the animal waste is used as organic fertilizer, and the rest is lost in handling. From the overview given in Table 3, it can be concluded that cattle manure has the greatest potential to be used as a source of clean energy and organic fertilizer. It can also be concluded that sustainable treatment of such resources is of vital concern for Egypt [5].

Table 1
Estimated crop residue generation and utilization in Egypt during the year 2004 [29].

Types of residues	Residue generation (per year)		Total utilization (per year)	
	(1000 t)	Percentage (%)	(1000 t)	Percentage (%)
Wheat straw	8212	30	8130	99
Rice straw	4968	18.2	1900	38.2
Maize residue	6655	24.3	5657–6322	85–95
Sorghum stalks	1272	4.6	1208	95
Barley straw	212	0.8	196	92.5
Cotton stalks	1252	4.6	626	50
Sugar cane residue	4793	17.5	3830	80
Total	27,364	100	21,284–21,949	77.8–80.2

Table 2
Major uses of crop residues [29].

Crop residue	Use
Wheat straw	Animal feed
Rice straw	Composting, animal bedding, vegetable storage, animal feed following treatment with urea or ammonia, and manufacture of construction products
Maize residues	Animal feed and fuel
Sorghum stalks	Animal feed and fuel
Barley straw	Animal feed
Cotton stalks	Fuel
Sugar cane residues	Animal feed, building material, industrial fuel, and paper manufacture

Table 3
Total production of animal wastes in Egypt [5,30].

Animal	Total waste (1000 t/year)
Cows	5403
Buffaloes	5097
Horses, asses, mules, and camels	2348
Sheep and goats	729
Chickens, ducks, and turkeys	<1
Total	13,578

3.3. Sewage waste

The sludge waste from urban and industrial sewage treatment plants comprises residuals that have serious effects on the environment. Due to the increasing population density and the currently low capacity for wastewater treatment prevailing in Egypt, a future increase in the number and capacity of wastewater treatment plants (WWTPs) can be expected. As a consequence, the amount of sewage sludge produced is also expected to increase.

Based on population studies and rates of water consumption, the total wastewater flows generated by all governorates in Egypt, assuming full coverage by wastewater facilities, were estimated by Lasheen and Ammar [32] at about 3.5 billion m^3/year. Approximately 1.6 billion m^3/year is treated, and additional treatment plant capacity equivalent to 1.7 billion m^3 is planned by the year 2017. Depending on the currently applied treatment technology, the amount of sewage sludge produced in Egypt was estimated at around 2 million tons/year of dry sludge in 2008 [33].

For many years, the methods and technologies implemented for sewage sludge treatment in Egypt were very limited. Recently, the application of anaerobic digestion technology for sludge stabilization and power generation was applied in Al Gabel Asfer WWTP. Windrow composting of dried sewage sludge is another type of sludge treatment that has been recently applied in Egypt, having been already applied in the Al Berka WWTP in Cairo and the (9N) site in Alexandria. These WWTPs are the largest centralized wastewater treatment plants in Egypt and produce more than 50% of the total dry sewage sludge produced in all of Egypt's WWTPs. The dried sludge from these plants is mainly reused in agriculture. About 0.66 million tons of the dried sewage sludge were sold to farmers in 2007, representing more than 85% of the total sewage sludge produced by all WWTPs in Egypt [33].

3.4. Municipal solid wastes

Municipal solid wastes, which comprise garbage, originate from residential, commercial, and institutional sources as well as construction, demolition, and municipal services [34]. In general, the more urbanized the area is, the higher the amount of waste generation per capita [35]. A positive correlation exists between increased welfare and generation of municipal waste [24].

Egypt generated an estimated 15.3 million tons of municipal solid waste in 2001, of which approximately 75% was generated in urban centers [36]. According to the Central Agency for Public Mobilization and Statistics, the estimated municipal solid waste generated in Egypt reached about 34.6 million tons in 2007.

The typical composition of municipal solid waste in Egyptian cities is shown in Table 4, where organic waste is the main component, representing 60% of the waste produced [16,25,35]. Eleven percent of the material is denoted as “other” and mainly includes construction and demolition debris and hazardous waste.

Between 30% and 50% of the municipal solid waste generated in developing countries is usually left unattended on the streets or vacant land plots [37,38]. In this sense the quantity of uncollected solid wastes in different governorates in Egypt reached a total of

25 million m^3 by 2004 [39]. Landfilling and incineration have recently been introduced in Egypt as more environmentally sound solid waste treatment techniques [25]. Sanitary landfilling is usually the lowest-cost option, as long as the required landfill area is available. There are no landfill regulations or standards that provide a basis for compliance and monitoring; however national guidelines for these standards are being prepared by the EEAA. The practice of sanitary landfilling is still in its infancy in Egypt [16].

4. Theoretical energy potential from biomass in Egypt

The information presented in the previous section has shown the high biomass production in Egypt, based on agricultural residues, animal waste, sewage waste, and solid waste. These could be used to produce bioenergy, reducing fossil fuel consumption and also improving the environment as a safe method of waste disposal. The theoretical energy potential from biomass in Egypt has been analyzed in this study. The results are summarized in the subsections below.

4.1. Theoretical energy from agricultural crop residues

To estimate the theoretical energy potential of crop residues, according to Klass [40], several parameters are necessary: theoretical annual crop production, annual theoretical residue production, availability, and dry weight. The collectible dry residue or dry biomass (D_b) is the theoretical biomass production in terms of weight. It is determined by Eq. (1) for a given crop. In this mathematical expression, A_{cp} is the theoretical annual crop production in tons, r is the residual factor that gives the total mass of residue when multiplied by the total country yield for that crop generated, a is the availability factor or availability of collectible crop residues as waste biomass, and w is the dry weight factor expressed as a percentage.

$$D_b = A_{cp} \times r \times a \times w \tag{1}$$

Table 5 shows agricultural crop production and dry biomass according to Eq. (1) based on agricultural crop production in Egypt for the year 2007 according to CAPMS [17]. The residue factor (r) and availability factor (a) have been considered following Klass [40]. The highest theoretical dry biomass production corresponded to rice (7.86 million tons/year).

Table 4
Typical composition of municipal solid wastes in Egyptian cities [16,35].

Waste composition	Percentage (%)
Organic waste	60
Paper	10
Plastic	12
Glass	3
Metals	2
Textiles	2
Other	11

4.1.1. The potential energy content

The potential energy content of the collectible dry residue (P_e) has been calculated using Eq. (2) [40], where D_b is the amount of residue, O_c its organic content expressed as a percentage, and HHV the higher heating value of the organic material.

$$P_e = D_b \times O_c \times HHV \tag{2}$$

Table 5 also shows the potential energy from biomass according to Eq. (2); the organic content (%) and HHV (18.6 GJ/dry tons) have been determined according to Klass [40].

Although wheat straw represents the highest amount among the crop residues and has considerable biomass and energy content, it was excluded from the mathematical analysis because 99% of it is used as animal feed. Barley straw was also excluded from the analysis because it is generated in low quantities and is mainly used as animal feed (Tables 1 and 2). So in this study, wheat and barley straw have not been included as suitable candidates for crop energy production in Egypt.

The analysis indicates that a total of 12.33 million tons/year of dry biomass could produce a theoretical energy of 185.75 PJ/year. The biomass that could give the highest theoretical energy production is rice (113.99 PJ/year). The rest of the crops include biomass with considerably lower potential energy content.

4.1.2. Potential energy of some residues in different forms

Considering the important role of biomass for energy production and its increasing importance in the transport sector, studies on biomass utilization and the production of bioenergy and biofuels should be undertaken. In Egypt, transportation fuels represent around 30.5% of the total fuel energy consumption. The availability of high energy materials in Egypt suggests that biofuel (especially ethanol) is highly feasible if there is access to proper low-cost conversion and fermentation technologies [41]. The use of lignocellulosic biomass residues as feedstocks (i.e. starting material) allows a substantial increase in the fuel ethanol production capacity and a reduction in the cost of ethanol production to a competitive level [42]. Rice straw, maize residues and sugar cane residues are the most abundant lignocellulosic agriculture wastes produced in Egypt and the most suitable candidates for biofuel production [41].

Table 6 shows the theoretical ethanol yield and energy content from rice straw, maize residues, and sugar cane residues; the theoretical ethanol yield and the energy content of bioethanol (19.6 MJ/L) have been calculated according to Aly and Megeed [41]. The total theoretical energy content of ethanol from these residues is about 94.8 PJ/year. Rice straw represents the highest value among these residues, accounting for about 67.5% of the total energy content. So, it is considered the most important of such residues and can be used as a clean fuel to decrease the dependence on crude

Table 5
Theoretical agricultural crop production, dry biomass, and potential energy in Egypt, calculated according to estimated crop production in 2007.

Crop	Production (A_{cp}) (1000 t/year)	Residue factor (r)	Available factor (a)	Dry weight % (w)	Dry biomass (D_b) (million tons/year)	Organic content (O_c)%	Energy content (P_e) (PJ/year)
Sugar cane	16,656	0.52	1.00	20	1.73	84	27.06
Rice	6868	1.43	1.00	80	7.86	78	113.99
Maize	5572	1.10	0.60	53	1.95	90	32.63
Sorghum	827	1.57	0.64	40	0.33	84	5.19
Cotton	621	2.45	0.60	50	0.46	81	6.88
Total					12.33		185.75

oil in the transportation sector and to provide an environmentally safe technology for the straw disposal. Not only ethanol but also other different forms of bioenergy can be recovered by biochemical conversion of rice straw through different available techniques, such as biogas from anaerobic digestion, syngas through gasification, or bio-oil from pyrolysis [43–45].

The potential energy based on the estimated amount of rice straw biomass has been estimated in the forms of bio-oil, syngas, and biogas. The bio-oil yield (68% of straw weight) and its heating value (19 MJ/kg oil) have been taken from Jung et al. [43], while the syngas yield (1.84 m^3/kg straw) and its heating value (6.01 MJ/m^3 gas) have been found according to Lyang et al. [44]. The heating value for biogas (6.81 MJ/Kg straw) was estimated according to Summers [45]. The estimated values of potential energy from bio-oil, syngas, and biogas were 101.55, 86.92, and 53.53 PJ/y, respectively. So, pyrolysis is the best technique for recovering energy from rice straw, followed by gasification, biochemical conversion, and finally anaerobic digestion.

4.2. Theoretical energy from animal waste

Animal waste has been mainly used as fertilizer [46–48]; however the anaerobic digestion of manure is known to have the potential to produce energy [49]. This technology has the potential to solve waste-handling problems while producing renewable gas, electricity, heat, and also fertilizer [50].

Using Xuereb's conversion factor of 130 MJ/gal [51] moreover, Cooper and Laing [52] estimated that the energy (biogas) produced annually from a single head of cattle is equal to 50 gallons of gasoline, and taking into account the total cattle population in Egypt as indicated above (6.248 million head of cattle), the theoretical total potential is 40.61 PJ of energy, which equals approximately half the amount of bioethanol energy that would be produced from lignocellulosic residues in Egypt.

4.3. Theoretical energy from sewage sludge

With improved control and treatment of industrial wastewater, sewage sludge can be utilized as a valuable fertilizer and soil conditioner as well as for energy production by collecting methane from sludge digestion, which can generate electricity in a secondary step [32,53].

In this study, theoretical electrical generation from 1 kg of dry sewage sludge has been calculated as 0.78 kWh/kg of dry sludge, assuming that the quantity of digested gas obtained during the anaerobic digestion is 1 m^3/kg of volatile solids destroyed and the lower heating value of the digested gas is approximately 6.22 KWh/m^3 [33].

Considering the theoretical sewage sludge production explained in Section 3.3 (2 million tons of dry sludge), the estimated annual theoretical electrical energy generated from 0.78 KWh/kg of dry sludge is about 1560 GWh. The average calorific value used in the energy calculation for sewage sludge is 2000 Kcal/ kg dry matter [14]. The potential energy from sewage sludge in Egypt can be estimated as about 16.74 PJ based on the indicated amount of sewage sludge and its average calorific value. Despite its minor energy content, it may contribute to an observed amount of the energy used to operate the WWTP that produces this sludge.

Energy production from sewage sludge is fairly well developed in Egypt. For example Al-Gabel Al-Asfer WWTP is the biggest wastewater treatment plant in Egypt, having a current sewage treatment capacity of 1.8 million m^3/day, which will be increased to 3 million m^3/day in 2020. The application of anaerobic digestion technology for sludge stabilization and power generation in Al-Gabel Al-Asfer WWTP has achieved good results and considerable experience of operation and maintenance has been gained. A large portion of the biogas produced is currently used for the operation of hot water boilers, which are used to heat the raw sewage sludge in the primary digesters. Dual fuel generators use the excess digested gas to generate electricity, representing about 37–68% of the power consumed by the WWTP. The digested sludge is dewatered, dried, and then reused in agriculture. Thus, there is an interest in using such technology on a large scale in Egypt, especially in big wastewater treatment plants in major cities [33].

Table 6
Ethanol production and its energy content from lignocellulosic biomass in Egypt.

Lignocellulosic biomass waste	Dry biomass (million ton/ year)	Ethanol yield (L/dry ton)	Ethanol production (million L/year)	Energy content (PJ/year)
Rice straw	7.86	416	3269.76	64.0
Sugar cane residues	1.73	424	733.52	14.4
Maize residues	1.95	428	834.60	16.4
Total	11.54		4837.88	94.8

4.4. Theoretical energy from municipal solid waste

Energy can be recovered from the organic fraction of waste through two methods: (i) thermo-chemical conversion by incineration and (ii) bio-chemical conversion by anaerobic digestion in which only the biodegradable fraction of the organic matter can contribute to the energy output.

4.4.1. Theoretical energy from thermo-chemical conversion by incineration

In thermo-chemical conversion all of the organic matter, biodegradable as well as non-biodegradable, contributes to the energy output. The power generation potential (P_{gp}) and the net power generation potential (NP_{gp}) from waste, both expressed in kilowatt hours, have been estimated using Eqs (3) and (4) [54], where W is the total quantity of waste (tons), NCV is the net calorific value (k-cal/kg), and CE is the conversion efficiency.

$$P_{gp} = \left(\frac{1000}{860}\right) \times W \times NCV \tag{3}$$

$$NP_{gp} = P_{gp} \times CE \tag{4}$$

In this study NCV has been considered as 1200 k-cal/kg when CE is 25% [54]. Taking into account the estimated amount of solid waste available in Egypt in 2007, the power generation potential becomes 48,279 GWh (173.8 PJ) and net power generation potential becomes 12069.8 GWh.

4.4.2. Theoretical energy from bio-chemical conversion through anaerobic digestion

In bio-chemical conversion, only the biodegradable fraction of the organic matter can contribute to the energy output. In this case P_{gp} and NP_{gp} from waste, both expressed in kilowatt hours, can be estimated by Eqs. (4) and (5) [54], where W is the total quantity of waste (tons), VS is the total organic/volatile solids (say 50%), OBF is the organic bio-degradable fraction (approx. 66% of VS), DE is the typical digestion efficiency (60%), BY is the biogas yield (0.80 m^3/kg of VS destroyed), CV is the typical calorific value of bio-gas (5000 kcal/m^3), and CE is the typical conversion efficiency (30%).

$$P_{gp} = \left(\frac{1000}{860}\right) W \times VS \times OBF \times DE \times BY \times CV \tag{5}$$

For 34.6 million tons of solid waste, the power generation potential is equal to 31864.2 GWh (114.7 PJ) and net power generation potential is 9559.3 GWh.

From the previous results it can be noticed that the power generation potential value obtained from solid waste using thermo-chemical conversion is greater than that obtained using biochemical conversion. This is because all of the organic matter, biodegradable as well as non-biodegradable, contributes to the energy output in thermo-chemical conversion. Meanwhile, in bio-chemical conversion only the biodegradable fraction of the organic matter can contribute to the energy output.

4.5. *Theoretical potential energy from biomass*

Table 7 summarizes the maximum theoretical potential energy that could be obtained from biomass wastes in Egypt, considering biomass from agricultural crops, sewage sludge, municipal solids, and animal waste. It is possible to conclude that the total theoretical energy production from biomass is 416.9 PJ, representing 92.6% of the total production in all installed power plants in Egypt nowadays.

Because of the large amount of residual biomass from agricultural crops and its considerable energy content, it represents the major part of the total theoretical energy (44.6%), followed by municipal solid waste (41.7%); on the other hand, animal waste accounts for about 9.7% and sewage sludge for only 4.0% of the total amount. Due to the increase in crude oil consumption and decrease in its production over the years, the potential energy of agricultural crop residues and solid waste may contribute to decreasing the consumption of crude oil by approximately 19% and 17.8%, respectively, based on its consumption amount, which is indicated in Fig. 2.

Finally, rice straw represents the most important agricultural biomass residue due to its large amount and high energy potential, accounting for about 61.5% of the potential energy of crop residues, and its energy can be recovered in different forms such as bioethanol, bio-oil, biogas, and syngas.

Table 7
Theoretical potential energy from biomass residues in Egypt.

Biomass type	Theoretical potential energy (PJ)	Percentage of total energy (%)
Agricultural crop residues	185.75	44.6
Animal wastes (cows and buffalo)	40.61	9.7
Sewage waste (sewage sludge)	16.74	4.0
Municipal solid waste	173.80	41.7
Total	416.9	100

5. Conclusions

The main sources of biomass waste in Egypt are agricultural waste (crop residues), followed by municipal solid waste, animal waste, and sewage waste. The amount of dry biomass produced from agricultural crop residues is about 12.33 million tons/year, and 63.75% of this amount is produced from rice straw.

According to the quantity of biomass waste calculated in this study and its energy content, agricultural crop residues represent the highest value of theoretical potential energy from the main biomass sources in Egypt; this source could produce 44.6% of the total theoretical energy potential. Agricultural crop residues are followed by municipal solid waste, which could produce 41.7% of the total theoretical energy potential from an annual amount of 34.6 million tons. Ethanol production from agricultural crop residues is a feasible option for second generation biofuel production in Egypt. Lignocellulosic agricultural wastes are cheap renewable resources and allow a substantial increase in fuel ethanol production capacity. Rice straw, maize residues and sugar cane residues are the most abundant lignocellulosic agricultural biomasses produced in Egypt, and represent the most suitable candidates for ethanol production. In this study, the total theoretical ethanol yield from these wastes is estimated at about 4837.88 million L/year, with an energy content of 94.8 PJ/year, of which 67.5% of the energy is represented by rice straw. As a consequence, crop residues, especially rice straw, would represent a good candidate as a renewable energy source in Egypt which could be used as a clean fuel and would decrease the dependence on fossil fuel; its energy can be recovered in other different forms such as bio-oil, biogas, and syngas.

Finally, buffalo and cow manure represent the major part of animal waste in Egypt. About 6.248 million head of buffalo and cows could produce 9.7% of the total theoretical energy. On the other hand, 2 million tons/year of dry sewage sludge accounts for only 4.0% of total theoretical energy production.

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References

[1] Vojdani F. Biomass and waste characterization as a potential energy sources in Iran. In: Proceedings of the third international symposium on energy from biomass and waste. Venice, Italy; 2010. p. 8–11.
[2] Youssef MA, Wahid SS, Mohamed MA, Askalany AA. Experimental study in Egyptian biomass combustion in circulating fluidized bed. Applied Energy 2009;86:2644–50.
[3] Khalil A, Mubarak A, Kaseb S. Road map for renewable energy research and development in Egypt. Journal of Advanced Research 2010;1:29–38.
[4] Sun Z, Jin Bao-Sheng J, Ming-Yao Z, Ren-Ping L, Yong Z. Experimental study on cotton stalk combustion in a circulating fluidized bed. Applied Energy 2008;85:1027–40.
[5] El-Mashad HM, van Loon WKP, Zeeman G, Bot GPA, Lettinga G. Reuse potential of agricultural wastes in semi-arid regions: Egypt as a case study. Reviews in Environmental Science and Biotechnology 2003;1:53–66.
[6] Murphy ML. Retrofit of coal-fired power boilers using fluidized bed biomass gasification. Energy products of IDAHO. Coeur d'Alene, Idaho, USA, 208; 2001. p. 765–1611.
[7] Ren J, Li F, Li Q, Wu J. Experiment study on the combustion characteristics of maize stalk biomass fuel. In: Proceedings of the 9th asia–pacific international symposium on combustion and energy utilization, China; 2008.
[8] Baird MS, Eng MA. Energy fact sheet. The energy educators of Ontario; 1993.
[9] Maiga AS, Chen GM, Wang Q, Xu JY. Renewable energy options for a Sahel country: Mali. Renewable & Sustainable Energy Reviews 2008;12:564–74.
[10] El-Khayat MM, Ameen EE. Renewable energy in Egypt—challenges and prospects. Thermal Issues in Emerging Technologies. ThETA 3. Cairo, Egypt; December 19–22, 2010. p. 277–80.
[11] Amigun B, Sigamoney R, Von Blottnitz H. Commercialisation of biofuel industry in Africa: a review. Renewable & Sustainable Energy Reviews 2008;12:53–68.
[12] Smeets EMW, Faaij APC, Lewandowski IM, Turkenburg WC. A bottom-up assessment and review of global bio-energy potentials to 2050. Progress in Energy and Combustion Science 2007;33:56–106.
[13] Zannoun MS. Egypt's renewable energy strategy, achievements and programs. New & Renewable Energy Authority (NREA), Egypt; 2009.
[14] NREA. Implementation of renewable energy technologies—opportunities and barriers. Egypt country study; 2002.
[15] EL-Shimy M. Viability analysis of PV power plants in Egypt. Renewable Energy 2009;34:2187–96.
[16] Bushra M. Regional study on policies and institutional assessment of solid waste management in Egypt. Blue Plan. Regional Activity Centre, Sophia Antipolis; 2000.
[17] CAPMAS. Central Agency for Public Mobilization and Statistics, 〈http://www.capmas.gov.eg/pages_ar.aspx〉? pageid=708; 2013 [accessed 02.13].

[18] El Saeidy E. Renewable energy in agriculture in Egypt. Technological Fundamentals of Briquetting Cotton Stalks as a Biofuel. Doctoral thesis. Berlin University; 2004.
[19] IndexMundi. Egypt Electricity, 〈http://www.indexmundi.com/egypt/electricity_production.html〉; 2012.
[20] Elmassry I. Sunny outlook in Egypt: potential and opportunities for cogeneration. Cogeneration and On-site Power Production. 〈http://www.powergenworldwide.com/index/display/articledisplay/273399/articles/cogeneration-and-on-site-power-production/volume-7/issue-5/features/sunny-outlook-in-egypt-potential-and-opportunities-for-cogeneration.html〉; 2006 [accessed 01.09.06].
[21] GTZ. Integration of large amounts of renewable electricity in the Egyptian energy grid – capacity building for management and engineer – technical level (Egypt-RE-Grid); 2010.
[22] Mahmoud SA. Electricity sector in Egypt. Egyptian Electricity Holding Company. DSM & EE workshop; 2009.
[23] Mat SB. Biomass energy utilization & environment protection—commercial reality and outlook. Transtherm Engineering & Construction Sdn Bhd. Malaysia; 2003.
[24] Karaj Sh T, Leis H, Müller J. Analysis of biomass residues potential for electrical energy generation in Albania. Renewable & Sustainable Energy Reviews 2010;14:493–9.
[25] EQI. Environmental Quality International. Alternative methods for solid waste management and treatment and disposal of wastewater. Environmental Services for Improving Water Quality Management. Ministry of Water Resources & Irrigation, United States Agency for International Development; 2005.
[26] Aref AA. Combustion characteristics of biomass fuels. Bulletin of Faculty of Engineering, Minia University 1995:126–38.
[27] Shehata AM. Effect of particle size and firing load on characteristics of heat transfer in square fluidized bed combustor. MSc. Cairo University, Egypt; 2002.
[28] NREA. Implementation of renewable energy technologies (RETs)—project opportunities and barriers. Egypt Country Study. Final Report to UNEP Collaborating Centre on Energy and Environment. Denmark: Risø National Laboratory; 2000.
[29] GTZ, International Services. Technical/policy note on agricultural waste management in Egypt; 2006.
[30] Hamdy YA. The current situation of Egyptian agricultural wastes. In: Proceedings of the anaerobic treatment of solid wastes workshop, Mansoura University, Egypt; 1998, p. 1–5.
[31] Maldonado J, Sherif S. Egypt livestock and products annual. GAIN Report. USDA Foreign Agriculture Service. Global Agriculture Information Network; 2010.
[32] Lasheen MR, Ammar NS. Assessment of metals speciation in sewage sludge and stabilized sludge from different wastewater treatment plants, Greater Cairo, Egypt. Journal of Hazardous Materials 2009;164:740–9.
[33] Ghazy M, Dockhorn T, Dichtl N. Sewage sludge management in Egypt: current status and perspectives towards a sustainable agricultural use. World Academy of Science Engineering and Technology 2009;57:299–307.
[34] Tchobanoglous G, Theisen H, Vigil S. Integrated solid waste management. New York: McGraw-Hill; 1993.
[35] Badran MF, El-Haggar SM. Optimization of municipal solid waste management in Port Said – Egypt. Waste Management 2006;26:534–45.
[36] CEA. Country Environmental Analysis (1992–2002). Arab Republic of Egypt, Water and Environment Department, the Middle East and North Africa Region. A World Bank Document; 2002.
[37] UNEP. United Nations Environment Programme. Global environment outlook, vol. 3. London: Earthscan Publications; 2003.
[38] Abdrabo MA. Assessment of economic viability of solid waste service provision in small settlements in developing countries: case study Rosetta, Egypt. Waste Management 2008;28:2503–11.
[39] EEAA. Egyptian Environmental Affairs Agency. Egypt state of the environment in 2004. Cairo, Egypt; 2005.
[40] Klass DL. Waste biomass resource abundance, energy potential, and availability.Biomass for renewable energy fuels and chemicals. USA: E-Publishing Inc; 1998 p. 137–58.
[41] Aly HF, Megeed EM. Lignocellulosic biomass conversion technologies to biofuels, potentials in Egypt. Report submitted to UNIDO. Cairo, Egypt: IMC; 2008.
[42] Reith JH, Uil H, et al. Co-production of bio-ethanol electricity and heat from biomass residues. In: Proceedings of the 12th european conference on technology exhibition on biomass for energy, industry and climate protection. Amsterdam, Netherlands; 2002.
[43] Jung S, Kang B, Kim J. Production of bio-oil from rice straw and bamboo sawdust under various reaction conditions in a fast pyrolysis plant equipped with a fluidized bed and a char separation system. Journal of Analytical and Applied Pyrolysis 2008;82:240–7.
[44] Liang C, Yi S, Yi C, Yong-hao L, Fang L, Wen-Guang W. Effect of equivalence ratio on gasification characteristics in a rice straw two stage gasifier. School of Mechanical Engineering, Shanghai Jiao Tong University, China; 2009.
[45] Summers DM. Using rice straw for energy production: economics, energetics and emissions. Department of Biological and Agricultural Engineering, University of California, USA; 2001.
[46] Basso B, Ritchie JT. Impact of compost, manure and inorganic fertilizer on nitrate leaching and yield for a 6-year maize–alfalfa rotation in Michigan. Agriculture, Ecosystems & Environment 2005;108:329–41.
[47] Schröder J. Revisiting the agronomic benefits of manure: a correct assessment and exploitation of its fertilizer value spares the environment. Bioresource Technology 2005;96:253–61.
[48] Kuligowski K, Poulsen TG, Rubæk GH, Sørensen P. Plant-availability to barley of phosphorus in ash from thermally treated animal manure in comparison to other manure based materials and commercial fertilizer. European Journal of Agronomy 2010;33:293–303.
[49] Wilkie AC, Castro HF, Cubinski KR, Owens JM, Yan SC. Fixed-film anaerobic digestion of flushed manure after primary treatment: wastewater production and characterisation. Biosystems Engineering 2004;89:457–71.
[50] Oregon EC. Dairy manure anaerobic digester feasibility study report. Albany; 2009.
[51] Xuereb P. Biogas—a fuel produced from waste. Available from: 〈http://www.synapse.net.mt/miwm/newsletter/3836.asp〉; 1997.
[52] Cooper CJ, Laing CA. A macro analysis of crop residue and animal wastes as a potential energy source in Africa. Journal of Energy in Southern Africa 2007;18:10–9.
[53] EIB. European Investment Bank. Cairo sludge disposal study. Mediterranean technical assistance programme for the execution of the Greater Cairo wastewater project; 1999.
[54] CPH & EEOC. Central Public Health and Environmental Engineering Organization. Manual on municipal solid waste management. Energy recovery from municipal solid waste. Ministry of Urban Development, Government of India; 2000.